

Karymshina, a Giant Supervolcano Caldera in Kamchatka: Boundaries, Structure, Volume of Pyroclastics

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Abstract—Data on a caldera discovered in 2006 are reported. The caldera formed in southern Kamchatka during Eopleistocene time (1.2 to 1.5 Ma). The caldera boundaries have been reconstructed and its dimensions determined (approximately 15×25 km). An uplifted block has been identified in the northwestern part of the caldera, the block is considered to be the result of emplacement of viscous rhyolite magmas at a later time (approximately 0.5–0.8 Ma), that is, as a resurgent uplift. We have reconstructed the boundaries of a large lacustrine basin that formed in the caldera after the appearance of the resurgent uplift. Calculations are provided yielding the volume of the pyroclastics ejected during caldera generation. It is shown that the caldera-forming eruption was a major one in Kamchatka in regard to its volume of ejected material, and ranks as a major eruption worldwide. We examined the structural controls of present-day hydrothermal systems and mineral occurrences situated in the area of study to demonstrate their relations to the caldera and the resurgent uplift.

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The notion of a supervolcano appeared quite recently in volcanological literature [5, 23, 28, 30, 31]. This is understood as a location of very large eruptions that eject volcanic rocks in amounts that are an order, or even two orders, greater than those due to ordinary volcanoes. Examples of supervolcanoes usually cited are the Toba complex on Sumatra, Indonesia and the Yellowstone in the United States. The former has dimensions of 100×30 km, the volume of acid pyroclastics ejected by it during the last phase of its formation alone, 74000 years ago, is 2800 km^3 [24]. The latter has dimensions of 85×45 km, the volume of material ejected by its last eruption is more than 1000 km^3 , and its age is 640000 years [25]. Eruptions like these are disasters for the entire ecosystem of the Earth, because vast spaces are covered with ash, and the climate becomes altered for decades following. If such an eruption were to take place in the Yellowstone Caldera now (this is quite possible during the coming decades in the opinion of some researchers), the result would be not only the destruction of most of the United States, but also effects on millions of people owing to lower temperatures, acid rains, and increased radiation. It is not by chance that supervolcanoes have attracted great interest in recent years, the next IAVCEI sitting, which will take place in Perugia, Italy in 2007 will have Large-Volume Eruptions in Earth History: Explosive Supervolcanoes (<http://www.iugg2007perugia.it>) as one of its main topics.

The largest eruptions in Kamchatka have so far been related to Quaternary calderas whose generation involved the discharge of up to $100\text{--}150 \text{ km}^3$ of acid pyroclastics [11]. Larger eruptions that could be

equated with the eruptions of known supervolcanoes discharging 1000 km^3 or more are not known to have occurred in Kamchatka. At the same time it has been hypothesized that such eruptions could have also occurred during an earlier period [13]. The hypotheses were based on the fact that numerous ash beds were penetrated by wells drilled off Kamchatka, with the thickest layers being 1.1–1.6 Myr old. Southern Kamchatka is one area where a supervolcano can be supposed to exist. An extensive area dominated by acidic rocks was found at the boundary of southern Kamchatka and the transverse Nachiki fold–block zone by geologic surveys carried out as early as the 1970s. These rocks were classified into a special dacite–rhyolite formation and the area where the rocks were found is regarded as a major volcanotectonic depression [12]. Subsequently our knowledge of the age and volume of this formation, as well as of the dimensions of the volcanotectonic depression, were substantially updated, considering that the area was previously little known. Recent publications [19, 20, 22] report new datings of rocks in the formation, providing evidence of its Eopleistocene age, and the dimensions of the depression, which until then had rather approximate boundaries, were considerably reduced (Fig. 1).

We conducted special investigations in 2004–2006 to refine the geologic structure of the area in question with a view to determining the structural settings of the Bol'she-Bannaya and Karymshina geothermal fields situated there. This work has established the actual boundaries of the depression in many places and determined its true outline, and also threw light on later volcanism and the reconstruction of the resurgent uplift

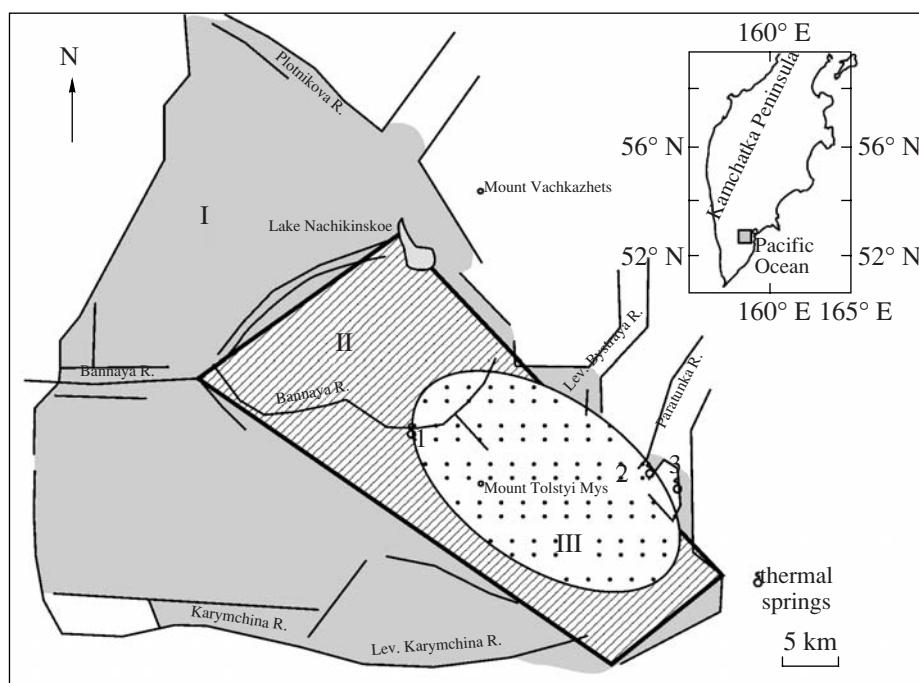


Fig. 1. Position of the Karymshina caldera and comparison with the volcanotectonic depressions that have previously been identified in the area: (I) Karymshina volcanotectonic depression [12], (II) Bannaya–Karymshina volcanotectonic depression [22], (III) Karymshina caldera (identified in this study for the first time). (1, 2, 3) Groups of thermal springs: (1) Bol'she-Bannaya, (2) Karymshina, (3) Verkhne-Paratunka. The inset in the top right corner shows the location of the area of study in Kamchatka.

associated with it. The upshot was that a large caldera that experienced resurgence should be identified in the area of study. At the present time all the boundaries of this structure have not been identified reliably, on one hand because it is large, and on the other hand because it is very old, so that its boundaries are not expressed in the topography and are partly overlain by more recent lavas. Nevertheless, it can be asserted even now that the caldera is the largest among the known Kamchatka calderas, having parameters that are close to those typical of structures now commonly called supervolcanoes.

The structure identified is close to, even though does not fully coincide with, the Bannaya–Karymshina volcanotectonic depression described previously [22]. In this connection, we shall call this structure by a new name—Karymshina Caldera—to avoid ambiguity (this is the name of a mountain range within the depression and of a river that flows through it).

General Information on the Area of Study and on the History of Study of a Sequence of Acid Tuffs and Ignimbrites in the Upper Reaches of the Bannaya, Karymshina, and Bystraya Rivers

The area of study is situated in the southern part of the Kamchatka Peninsula, about 50 km southwest of the town of Petropavlovsk-Kamchatskii. It is a mountain massif containing several summits as high as 1200–1300 m (Fig. 2). The highest is Mount Tolstyi

Mys (1343 m). Many rivers originate on the slopes of this mountain and nearest summits, flowing both eastward to the Pacific Ocean (Paratunka and Lev. Bystraya rivers) and westward to the Sea of Okhotsk (Bannaya and Karymchina). Further north is the Lake Nachikinskoe depression.

The area of study is west of the volcanoes of the East Kamchatka volcanic belt. The nearest and largest volcanoes, Gorelyi (1828 m) and Vilyuchinskii (2173 m), are situated to the southeast of the area of study.

Structurally speaking, the area is situated at the junction between the northwest trending Nachiki fold-block zone situated to the northeast and the Kambal–Gorelovskii graben to the south of it. The boundary between the two features is the so-called Vilyuchinskii lineament, which is a large northwest trending fault zone that traverses all of southern Kamchatka [2]. I.D. Petrenko [14] identified two parallel normal faults in the area, which he treats as part of the extended South Kamchatka system of mineralization-controlling normal faults that separate the uplifted areas in the northeast and east from the subsided areas in the south.

The map of the top of the Cretaceous basement for southern Kamchatka compiled by M.I. Zubin [8] shows that the area involves a basement low down to depths of 3.5 km or greater (Fig. 2). The local depression feature is also identified in the area from gravity data [3].

The zone of occurrence of acid tuffs and ignimbrites, which occupy much of the area, has a limited

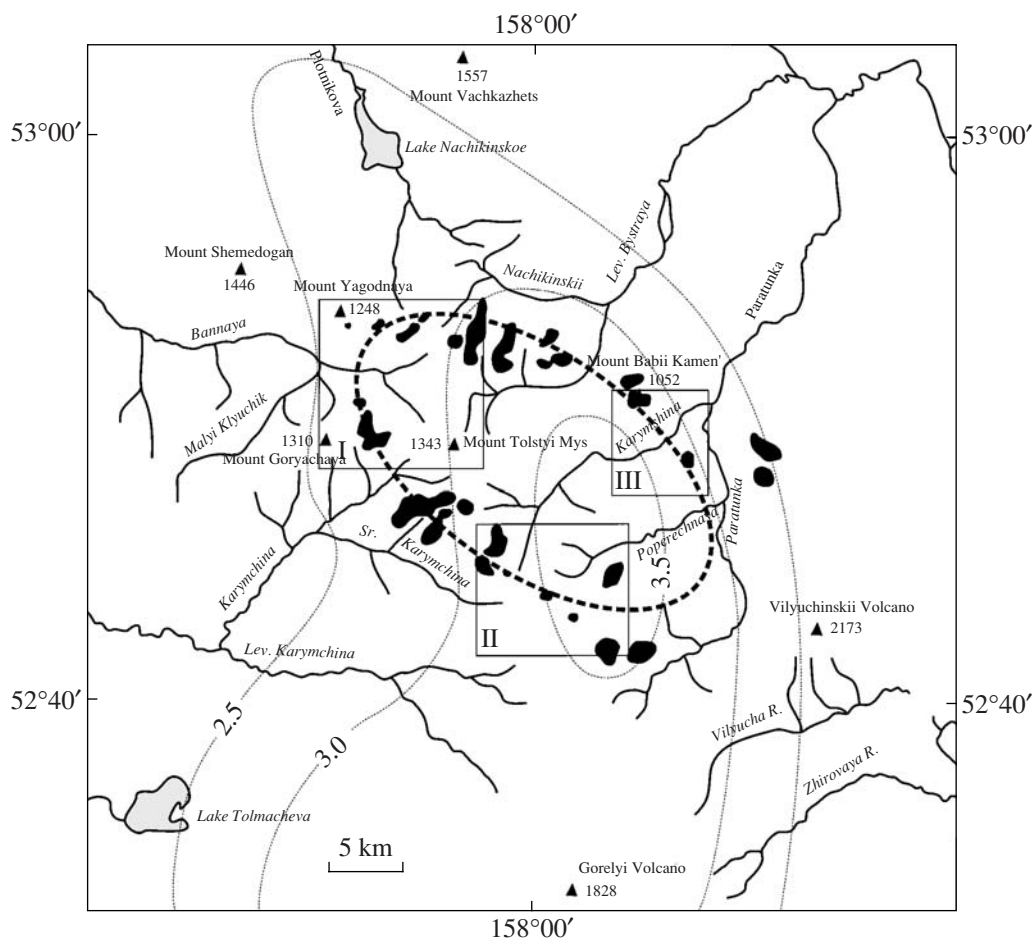


Fig. 2. Reconstructed boundaries of Karymshina caldera (solid dashed line). Rectangles mark areas that have been studied in detail: (I) upper reaches of Bannaya R., (II) Karymchina–Karymshina pass, (III) Babii Kamen'. Black spots mark rhyolite extrusions that were emplaced during the postcaldera phase. Light dotted lines are isolines of depth to top of Cretaceous basement [7], in km.

extent, with the zone clearly extending northwest. Its dimensions are 50×20 km. V.S. Sheimovich [18] classified the acid rocks found in the area as belonging to the Middle Miocene Berezovskii series on the basis of the geological mapping and research carried out by a team headed by M.A. Favorskaya [17] in 1958–1962. The area where these rocks are exposed was estimated to be 1000 km^2 , the thickness of the Berezovskii series being about 1000 m. The proportion of ignimbrites was estimated as 25% and the volume of acid rocks as 300 km^3 .

It should be noted that previous publications classified the large volcanic edifices situated around the acid rock field (the volcanoes of mounts Shemedogan, Shapochka, Goryachaya, etc.) and numerous larger extrusions and liparite flows occurring in the field of tuffs and ignimbrites as belonging to the Alnean series of Upper Miocene–Pliocene age [4, 16, 18].

When an intermediate-scale geological survey was carried out in the area in the late 1970s, the notion of a Berezovskii series was discarded, while the acid tuffs and ignimbrites were divided into several formations,

namely, the Upper Miocene liparite–dacite (ignimbrite) formation, the Late Miocene andesite–basalt, and the contrasting Late Miocene basalt–liparite formations [12]. The large Karymshina volcanotectonic depression, a triangle with sides of 45–50 km, was identified (Fig. 1). It was generally thought that it was bounded by normal faults with displacement amplitudes as large as 1000 m, the center of the depression being mostly filled with Middle Miocene ignimbrites whose K–Ar age was determined as 18–27 Myr [12]. The volcanoes of mounts Shemedogan, Shapochka, Goryachaya, Yagodka, etc., were thought to date back to the Late Miocene–Pliocene and the liparite extrusions to the Pliocene [12].

Later, the formation analysis was applied to the study of Kamchatka volcanic belts [21]. Three pre-Quaternary volcanic formations were identified in southern Kamchatka: (1) a Miocene andesite–basalt, (2) a Miocene–Pliocene liparite–dacite, and (3) a Pliocene andesite–basalt formation. The acid tuffs and ignimbrites of the area were classified as belonging to the Miocene–Pliocene liparite–dacite formation. It was

noted that, in contrast to the other formations, this one has a limited extent and shows a clearly defined north-west trend. It was found that the rocks of this formation occupy a zone of about 50×20 km; the zone itself has been called the Bannaya–Karymshina zone [21].

Sheimovich and his colleagues obtained new evidence of the K–Ar age for rocks in the area in the early 1990s [14, 15, 20]. These determinations were used as the basis for reducing the age of the Bannaya–Karymshina acid tuffs and ignimbrites to make them as young as Eopleistocene [20]. The age of the rhyolite extrusions was determined as Quaternary, 0.5–0.8 Ma [19, 20]. The new datings and the dramatic decrease in the age of the dacite–rhyolite formation led to the identification of a distinct Karymshina volcanic complex [22]. The complex was thought to include the thick sequence of acid tuffs and ignimbrites identified in the area of study previously, along with the numerous subvolcanic bodies found in the field of acidic rocks. The rocks in the Karymshina volcanic complex tend toward a large volcanotectonic depression (Bannaya–Karymshina), in the opinion of the workers who first identified the complex [22]. The depression was delineated by very approximate boundaries (Fig. 1); it was not considered by these authors as a caldera, with the tuffs and ignimbrites being thought to be related to the extrusions, on the hypothesis that the Karymshina complex rocks are due to areal extrusive volcanism [22]. At the same time, as mentioned by these authors themselves, the Karymshina complex is thus far little known: its structure has not been determined, there is no complete petrochemical composition and no clear knowledge of the boundary of the depression.

Overall, great uncertainty still prevails as to the geology of the study area, the stratigraphy of the constituent rocks, and the evolution of the relevant volcanism. All previous information must be revised. This primarily concerns the relationships of the acid tuffs and ignimbrites to the volcanoes of mounts Shemedogan, Shapochka, Goryachaya, Yagodnaya, etc., situated along the edge of these tuffs and ignimbrites. Until recently, all geological maps unambiguously marked these volcanoes as younger volcanoes [6, 12, 16, 18, 22]. The new evidence of the age of the acidic rocks in the area of study undermines these views. The acidic rocks, being of Eopleistocene age, must be younger than the volcanoes, and the latter should be regarded as evidence of a major volcanic phase preceding the generation of ignimbrites.

On the other hand, the position of the rhyolite extrusions and flows should be reconsidered; these were first supposed to belong to the Alnean Upper Miocene–Pliocene complex [4, 16], and later, as being part of the contrasting Late Miocene basalt–liparite formation [12]), as its later phase [21], with recent research insisting on areal extrusive volcanism, the most recent in the area, as its origin [19, 20, 22].

Identification of a Depression Boundary in Several Areas

We shall briefly discuss the geological structure of three areas we have studied in detail. The rocks of the Karymshina complex which fill the Karymshina caldera are of one and the same type in all the three areas; they are mostly ignimbrites or crystalline clastic tuffs saturated with fragments of plagioclase, quartz, and biotite, which make up 45–50% of the entire rock volume. Plagioclase prevails, its largest fragments are as large as 1.5–2 mm, with the more common size being within 0.5 mm. Both individual grains and fragments of monomineral aggregates are encountered. The phenocrysts are affected by fritting and resorption, and contain melt inclusions. The quartz is in the same state. Biotite (0.3–0.5 mm) forms flaky grains and thin laths, occasionally curved and split ones. Some grains show disintegration textures at the edges with mineralizing and feldspar minerals excreted. The groundmass consists of brown devitrified glass with preserved outlines of ash particles. The rock composition corresponds to rhyolite and has a 70–72% SiO_2 content.

The Upper Reaches of the Bannaya River area.

The youngest formations in the upper reaches of the Bannaya River and in the Bol'she-Bannaya steam-hydrothermal field were previously considered to be the volcanoes of mounts Goryachaya and Yagodnaya [16]. It was thought, in particular, that the large rhyolite extrusions in mounts Sunduk, Zub'ya, etc., represent one of the last manifestations of acid volcanism associated with the volcano of Mount Goryachaya. A magma chamber was supposed to exist beneath that volcano, with the chamber being the source of heat for the thermal water that is being discharged in the Bol'she-Bannaya field area [9]. Today these notions should be revised.

Based on the new datings of rocks in the Karymshina complex [19, 20, 22] and on field observations, we came to the conclusion that the ignimbrites that widely occur in the upper reaches of the Bannaya River and the rhyolite tuffs that belong to the Karymshina complex fill a major depression. They are much younger than the lavas that compose the volcano of Mount Goryachaya (Fig. 3). The extrusions of mounts Sunduk and Zub'ya, as well as other cutting rhyolite bodies, are even younger; they are of Middle Pleistocene age [19] and are totally unrelated to the volcanoes of mounts Goryachaya, Yagodnaya, etc. These extrusions have penetrated into the depression and mostly tend to occur at the depression boundaries (Fig. 3).

Several features should be noted in the disposition of rocks in the Karymshina complex for the area considered. In the first place, the rocks are found in many places to be adjacent to the lavas that compose the volcanoes of mounts Goryachaya and Yagodnaya, and to wedge out on their slopes (Fig. 4). No rocks of that complex have been detected in the Bannaya River valley downstream of the Bol'she-Bannaya Springs. Sec-

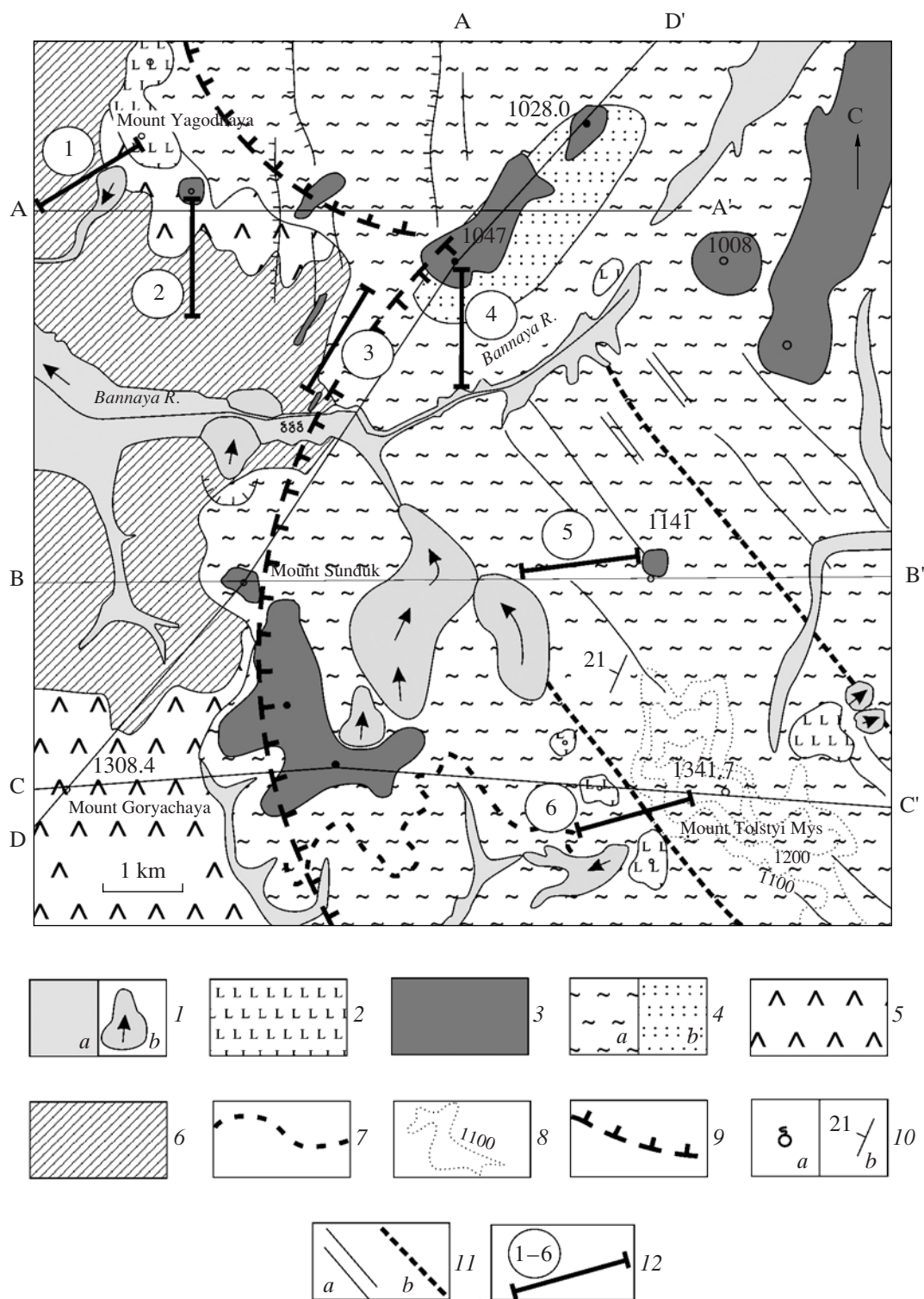


Fig. 3. Geological structure (A) and geological cross-sections (B) for the upper reaches of Bannaya River area: (1) deposits in river valleys (a) and landslides (b) (Upper Pleistocene–Holocene), (2) small volcanic structures composed of basaltic lavas (Middle Pleistocene), (3) extrusions, dikes, and flows consisting of rhyolites and rhyodacites (Middle Pleistocene), (4) tuffs and ignimbrites of the Karymshina complex (a) (Eopleistocene), tuff sandstones and tuff aleurolites—lacustrine deposits (b) (Lower Pleistocene), (5) dacite lavas that compose the massifs of mounts Goryachaya and Yagodnaya (Upper Pliocene), (6) undissected Oligocene/Pliocene deposits, (7) marker horizon of dacite lavas in the Karymshina complex, (8) relief isolines in the Mount Tolsty Mys area (m), (9) reconstructed boundaries of large depressions filled with Karymshina complex rocks, (10) thermal springs (a), attitude parameters (b), (11) faults: (a) fractures and normal faults, (b) reverse faults that bound the Mount Tolsty Mys uplift, (12) locations of cross-sections (1–6) shown in Fig. 5. The upward arrow in Fig. 3b marks the Tolsty Mys uplift.

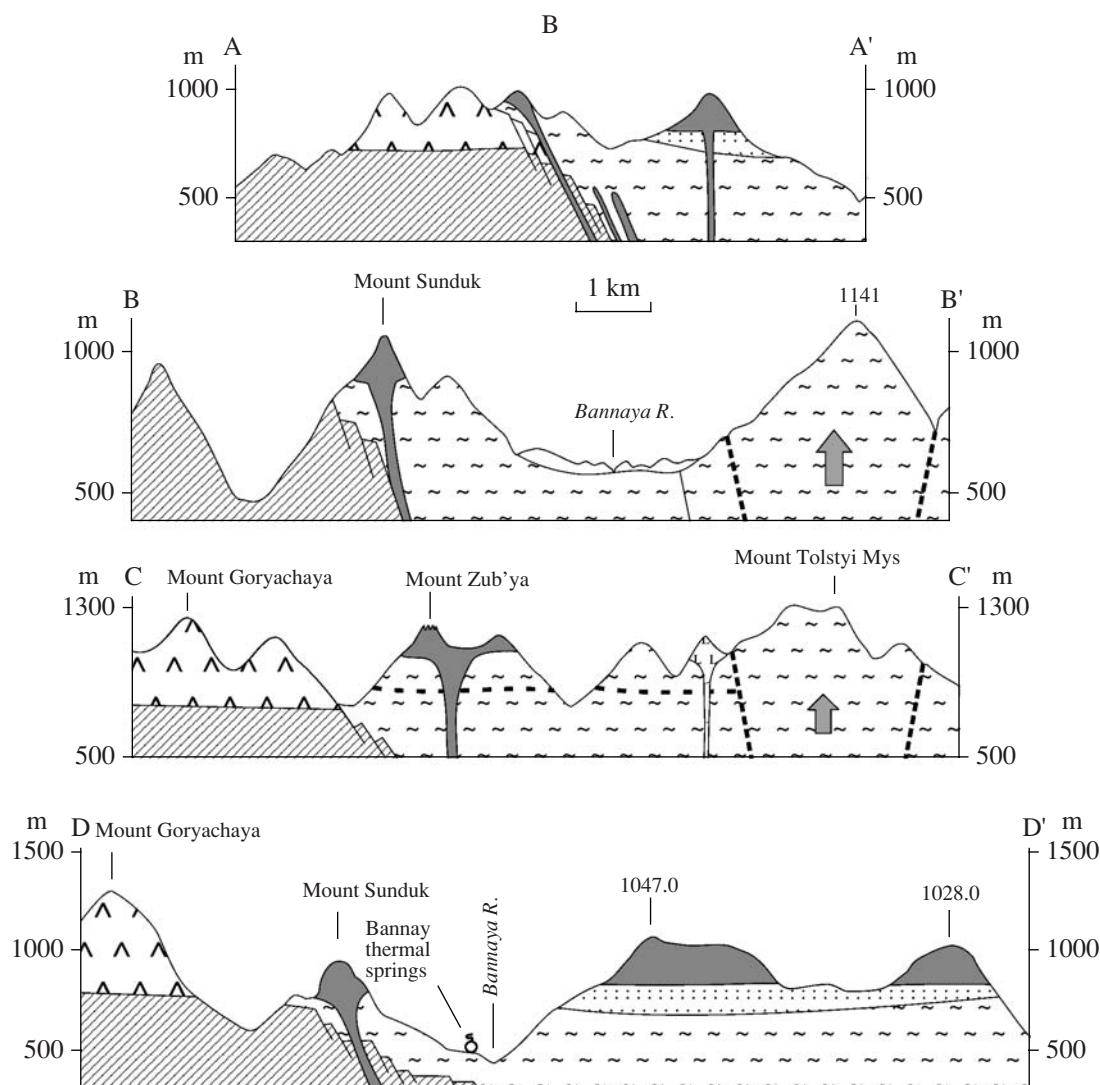


Fig. 3. Contd.

only, the Karymshina complex shows a dramatic increase in thickness to the east of mounts Goryachaya and Yagodnaya where the total visible thickness of these deposits exceeds 1000 m (Fig. 5). Thirdly, an extended volcanic glass bed 20–25 m thick was detected among the tuffs in the upper reaches of the Pravaya Karymshina River, and the bed can be considered as a marker horizon. It was followed along the north slopes of the Pravaya Karymshina River valley for a length of 7–8 km and found to be horizontal.

Special mention is due to the massif of Mount Tolsty Mys. Previously that uplift was thought to be a volcano of Miocene age, and it was believed to be one of the oldest volcanoes in the area [16]. Our research showed that Mount Tolsty Mys is the highest in the area and is composed of the same tuffs and ignimbrites of the Karymshina complex as the adjacent areas (Fig. 3). Its distinguishing feature consists in the fact that the rocks of the complex are much higher on Mount

Tolsty Mys and have a different attitude (Figs. 5, 6). We regard Mount Tolsty Mys as an uplifted block. The uplift is bounded by northwest trending faults that have clear expression in the relief. In addition, numerous smaller volcanoes and extrusions of basaltic and andesite-basaltic composition formed along the boundary of the uplift, both in the southwest and northeast, providing evidence of long-lived, deep-seated, permeable zones situated along the uplift boundaries. Our profiles can be used to estimate the amplitude of the Tolsty Mys uplifted block, which is at least 200 m (Fig. 3).

Based on the layering of deposits in the Karymshina complex, we think that the Bannaya–Karymshina depression has a nearly north–south boundary in the area of study. The boundary passes from the upper reaches of the Pravaya Karymshina River along the foot of Mount Goryachaya toward the Bol'she-Bannaya Springs and further northeast along the valley of a brook to a mountain pass situated near the 1047.0-m



Fig. 4. Karymshina complex tuffs and a small lava flow lying inside them, adjacent to precaldera lavas (slopes of Mount Yagodnaya). Dashed line shows the contact between precaldera and postcaldera deposits.

extrusion. That part of the depression boundary forms an arc with a radius of approximately 7 km and a center near the northern foot of Mount Tolsty Mys. The boundary deviates westward in the north of the area considered, where the edge of another depression seems to be located whose center is north of the Bannaya area.

The Pereval (Pass) area. This area is situated near the divide of the Karymshina and Karymchina rivers. The deposits of the Karymshina volcanogenic complex in this area occupy the entire northern part situated in the upper reaches of the Karymshina, Ovrazh'ya, and Poperechnaya rivers (Fig. 7). No rocks of the complex have been found further south, in the upper reaches of the Srednyaya and Levaya Karymchina rivers. Accordingly, the boundary of the Bannaya–Karymshina depression passes there along the divide ranges,

approximately east–west. Rocks of this complex have been found in the near-divide part as high as absolute altitudes of 1000–1100 m, with thin-bedded lacustrine deposits (tuff aleurolites and tuff sandstones) being detected at many locations in the upper part of the relevant cross-sections. Overlap has been found to be ubiquitous between rocks of the complex and the lavas that are remnants of the volcanoes which formed the depression walls (Fig. 8).

Similarly to the preceding area, there are abundant extrusive domes, dikes, and remnants of short lava flows composed of rhyolite and rhyodacite near the depression boundaries. These frequently compose dividing crests (Fig. 8).

In the southern part of the area we found ignimbrites of the Karymshina complex on the outer slope of the depression: the ignimbrite layer dips steeply southwest, following the relief (Fig. 7). This is one of the few areas where ignimbrites have been preserved in the sinking of the depression wall, this being a situation that is quite common in many calderas in Kamchatka and worldwide [11, 27].

The wall of the Bannaya–Karymshina depression in the area under consideration is composed of the remnants of several volcanoes whose structures have largely been destroyed, but can be reconstructed using elements of the attitude of the lavas that compose the volcanoes. Two structures are conspicuous on the left bank of the Srednyaya Karymchina River. One is a large volcano which Sheimovich previously identified [18] and named Lev. Karymchina Volcano (altitude 1434.9 m). The other volcano is to the east of this, its highest altitude is 1174.0 m. The two volcanoes have

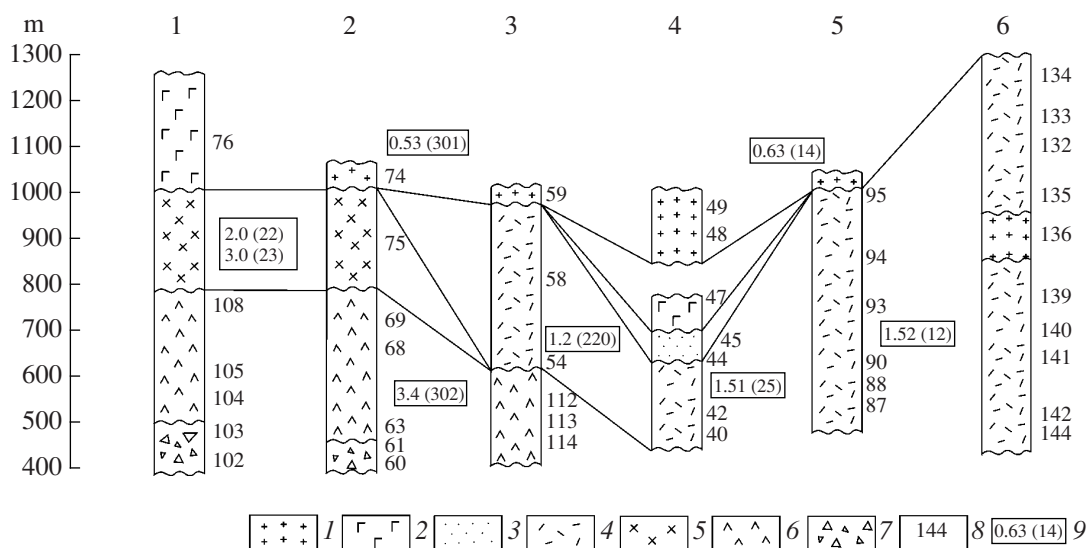


Fig. 5. Comparison between the deposits exposed in the walls of Bannaya R. and on slopes of Mount Tolsty Mys. Location of cross-sections (1–6) is shown in Fig. 3A: (1) rhyolites, (2) basalts, (3) tuff sandstone and tuff gravelite, (4) ignimbrites, crystalline clastic tuffs, (5) dacites, (6) andesites (subvolcanic bodies), (7) tuffs and tuff breccia, (8) sample numbers, (9) K–Ar age, Ma, sample number is in parentheses, after [19].

lava compositions ranging between basalts and andesites. Northeast of them is a northwest trending band consisting of three small volcanoes (of diameter 3–4 km) having lavas with compositions between dacite and rhyolite (Fig. 9). It is these structures which make the wall of the Bannaya–Karymshina depression in the area under consideration.

The Babii Kamen' area. The geological structure of this area is well known [7, 16, 17]. The rocks of the Karymshina rhyodacite complex are represented there by a thick sequence of densely welded ignimbrites (Fig. 10). The uppermost part of the Karymshina complex cross-section is here occupied, similarly to the preceding area, by thin-bedded deposits of lacustrine origin (tuff aleurolites and tuff sandstones). Taken as a whole, the Karymshina rocks compose the entire cross-section (about 1000 m thick) in the west of the area and wedge out gradually toward the east part of it (Fig. 10). The boundary of the Bannaya–Karymshina depression thus passes approximately across the center of the area, near the extrusions of mounts Goryachaya and Babii Kamen'. The extrusive domes themselves, similarly to the larger domes in the other areas described above, are composed of the same quartz–biotite rhyolites. Also, similarly to the other areas considered, the domes seem to be situated on the faults that bound the Bannaya–Karymshina depression, which, in the case under consideration, are on those which define its eastward limit.

A Discussion of the Data

The new data quoted above on the geological structure of the three areas situated in the upper reaches of the Bannaya and Karymshina rivers and near the Karymshina River, suggest the existence of a large depression which must be regarded as a resurgent caldera. It is elongate in the northwest direction and has the following dimensions: 15 km along the minor axis and 25 km along the major axis (Fig. 11); it is thus the largest caldera of those now known to exist in Kamchatka. The distinguishing feature peculiar to this structure among the other calderas known to exist in Kamchatka is the fact that a major uplifted block (a resurgent dome) has been reconstructed in the northwest of the depression. It is by now firmly established that the uplifted block is elongate in the northwest direction and is approximately 4 by 12 km in size. The uplift amplitude is estimated to be 200 m. The block has well-defined tectonic boundaries, being bounded by faults trending northwest and northeast.

The reconstruction of the lakes that filled the caldera. Although most of the caldera is filled with ignimbrites and acid tuffs more than 1000 m thick, an extensive sedimentary field has been identified in the southeast of the caldera, namely, sandstones and aleurolites above the tuffs and ignimbrites. The top of these deposits is everywhere at absolute altitudes of 1000–1100 m; from this it can be hypothesized that the surface of the lake that had filled the caldera was at this

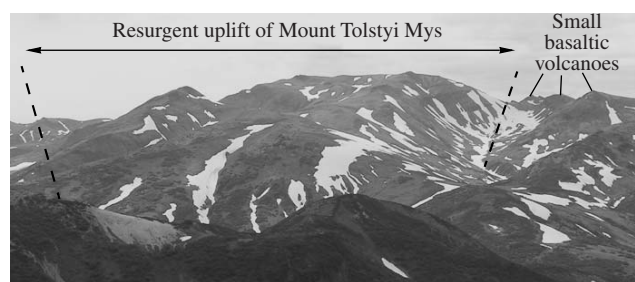


Fig. 6. View of Mount Tolsty Mys from northwest. Marked are boundaries of the resurgent uplift and a number of small basaltic volcanoes situated along the southwestern boundary of the uplift. On the slopes of Mount Tolsty Mys are ignimbrite beds steeply dipping northward.

level in the past (Figs. 3, 7, 10). The presence of sedimentary facies shows that a large lake existed after the formation of the caldera in its southeastern part. Lakes may have existed in other parts of the caldera also, since thin lacustrine deposits were encountered, in particular, in its northernmost part (Fig. 3).

Postcaldera volcanism. Another feature of this caldera is also the fact that numerous rhyolite domes were emplaced along its rim during the postcaldera time (Figs. 2, 11). Some of the domes are associated with thick lava flows which dip at low angles from the caldera center to the rim. The wide occurrence of rhyolite domes in the area has long been known, some domes have been studied in sufficient detail [4], but the structural setting of the domes was not clear, with these features being usually regarded as a result of areal rhyolite volcanism [22]. At the present time it can be asserted that the majority of the domes are situated in the caldera, mostly close to the caldera rim. The larger domes occur at the edges of the resurgent block. A dome with a flat summit (altitude 850 m) found in the south of the caldera is situated on the strongly eroded surface of tuffs and ignimbrites that fill the caldera (Fig. 7, cross-section B–B'). This fact demonstrates that the rhyolites were also emplaced much later than the origin of the depression, when its fill had been strongly eroded.

The caldera age. The available data on the age of the tuffs and ignimbrites in the Karymshina volcanic complex [19, 20] suggest 1.2–1.5 Ma for the generation of the caldera. The age of the rhyolites that compose the numerous domes situated inside and along the rim of the caldera is 0.5–0.8 Ma based on available data [19, 20]. It can be supposed that the resurgent uplift originated in the caldera at that time.

The rock volume erupted at the generation of the caldera. The volume of pyroclastics ejected at the generation of this caldera is hard to estimate, because it has been largely destroyed by erosion. It can be approximately estimated based on the caldera dimensions and on the calculations given in [28].

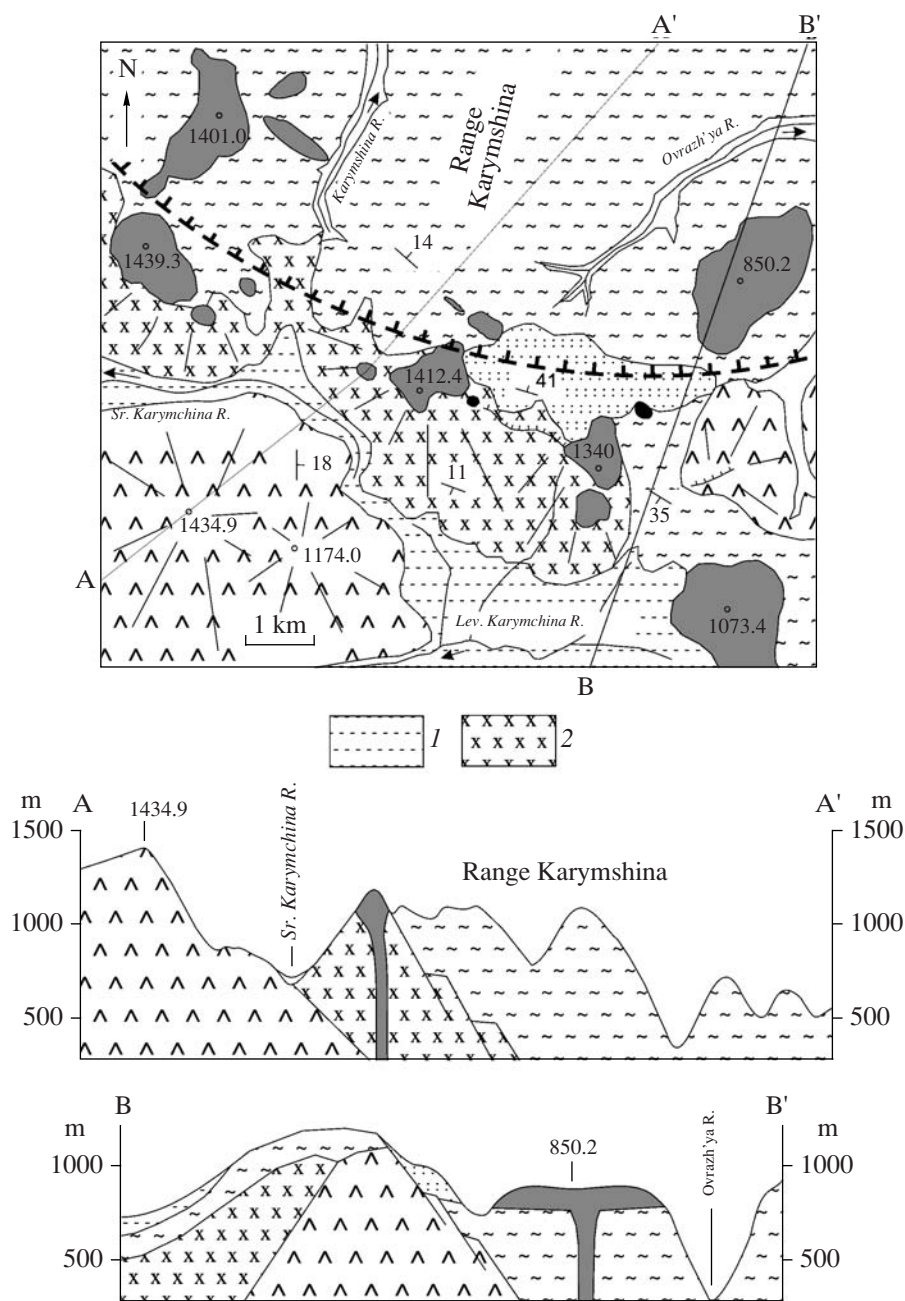


Fig. 7. Map of geological structure and geological cross-sections in the Pereval area: (1) ignimbrites of Gorelyi Volcano (Upper Pleistocene), (2) rhyolite and rhyodacite lavas that compose a number of small structures situated along the southern boundary of the Karymshina caldera (Upper Pliocene). For the other notation see Fig. 3A.

It is a known fact that the erupted material due to the generation of a large caldera is deposited, first, inside the caldera itself; secondly, in the form of ignimbrite sheets around the caldera; and thirdly, as ash that can be transported to great distances. The total volume of erupted material is the sum of these three components. Almost all known major ignimbrite-generating eruptions took place long ago (millions of years). In particular, Mason et al. [28] distinguished two periods of particularly frequent eruptions of this kind, 1 to 13 Ma and

25 to 37 Ma. Most of the material that was ejected by these eruptions has by now been eroded or buried by younger deposits. For this reason we are more often than not unable to calculate the true volumes of erupted material, but still are in a position to make some indirect estimates of them.

Based on the calculations given in [26, 28, 32], it can be approximately assumed that the three components in the total volume of erupted products associated with major calderas, viz., intracaldera fill, ignimbrite

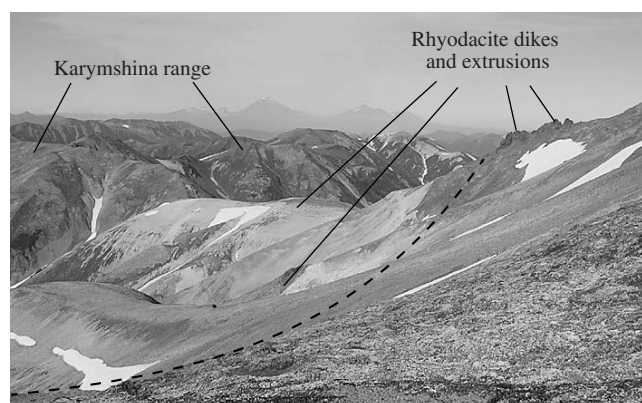


Fig. 8. Contact between the Karymshina complex deposits (left) that compose Karymshina Range and fill the Karymshina caldera and the older rocks that compose the caldera wall (right). Marked are numerous dikes and small rhyodacite extrusions confined to caldera boundary.

sheets around calderas, and the ash transported to great distances, are approximately equal when converted to compact rock. Proceeding from these assumptions, and knowing the volume of intracaldera deposits for the caldera under study (about 300 km³), we can estimate the total volume of associated rock. The volume of intracaldera fill when converted to compact rock (assuming the magma density to be 2.4 g/cm³ and ignimbrite density 2.2 g/cm³) is found to be 275 km³. The total volume of material ejected during the generation of this caldera must then be about 825 km³.

Mason et al. [28] have proposed classifying eruptions which have discharged more than 10¹⁵ kg as the largest explosive eruptions on Earth. In recent years it is just such eruptions that began to be called supereruptions, and the associated locations supervolcanoes [5]. The review [28] cites 47 such eruptions occurring worldwide during the period from the Ordovician to the Pleistocene. The generation of the caldera described in the present paper is fully entitled to be termed a supereruption, since the total weight of erupted material must have been 2 × 10¹⁵ kg based on the total erupted volume (825 km³). When the size of an eruption is estimated based on its magnitude [29], then eruptions of magnitude 8 or greater must be classed as the largest, according to [28]. The magnitude of the eruptions that were occurring during the generation of the caldera in the area of study can be estimated as 8.1–8.3 [28].

The structural setting of present-day hydrothermal systems. The area of study contains several groups of thermal springs: the Bol'she-Bannaya, Mal. Bannaya, Karymchina, Karymshina, and Verkhne-Paratunka ones. The largest are the Bol'she-Bannaya springs; these were investigated extensively by many different methods during the 1970s, wells were drilled and a hydrothermal power station was envisaged in the future. The hypothetical model of the hydrothermal systems situated in the drainage areas of the Bannaya

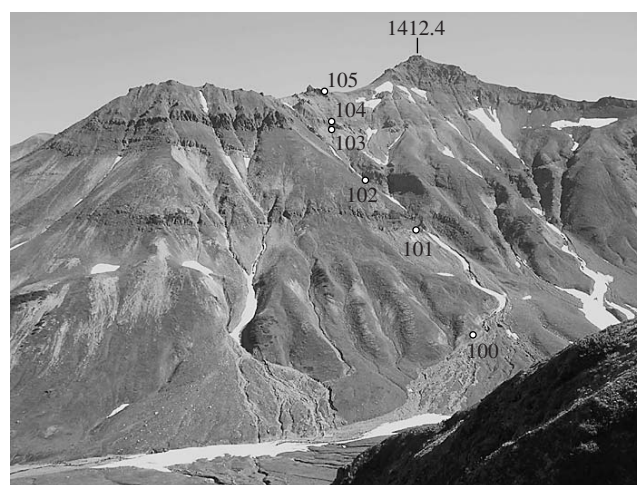


Fig. 9. A view of a small precaldera volcano in the upper reaches of the Sr. Karymshina R. One can see bluffs composed of dacite and rhyodacite lavas with intervening tuff beds. Near the summit ridge (site 105) are rhyolite extrusions emplaced later, during the generation of the Karymshina caldera. Numerals denote observation sites.

and Karymshina rivers developed at that time [9] supposed that a magma chamber beneath Mount Goryachaya was the source of those thermal waters. It was also supposed that the thermal supply of such systems is provided by endogenous fluids, in accordance with the concepts previously put forward by V.V. Aver'ev [1].

The reconstruction of the boundary to the large caldera that exists in the area yields a different setting of the present-day hydrothermal systems, in particular, of the Bol'she-Bannaya system. As has been demonstrated above, the volcano of Mount Goryachaya is an old one, so there is no reason to suppose the existence of a magma chamber beneath it at the present time to supply heat to hydrothermal systems. On the other hand, the caldera boundary has been found to pass through the Bol'she-Bannaya springs area (Figs. 3, 11). It was also found that numerous emplacements of acid lavas (domes, dikes, short lava flows) occur at the boundary throughout its length, these formations being rather young, less than 0.5–0.8 Ma [19]. These data suggest that the present-day hydrothermal activity in the area is related, on the one hand, to increased crustal permeability at the caldera boundary (due to the faults that exist there), while on the other hand, the large magma chamber existing in the area (above which the caldera was generated in the Eopleistocene followed by a resurgent dome in the Lower/Middle Pleistocene) retains its heat and continues to supply it to the fluids and water that are circulating around it. It thus appears that the setting of the Bol'she-Bannaya hydrothermal system is controlled by the deep incision of the Bannaya River valley which traverses the caldera rim in the northwest (Figs. 3, 11). The setting of the Karymshina hydrothermal system is controlled by the deep incision of the Karymshina River valley which traverses the

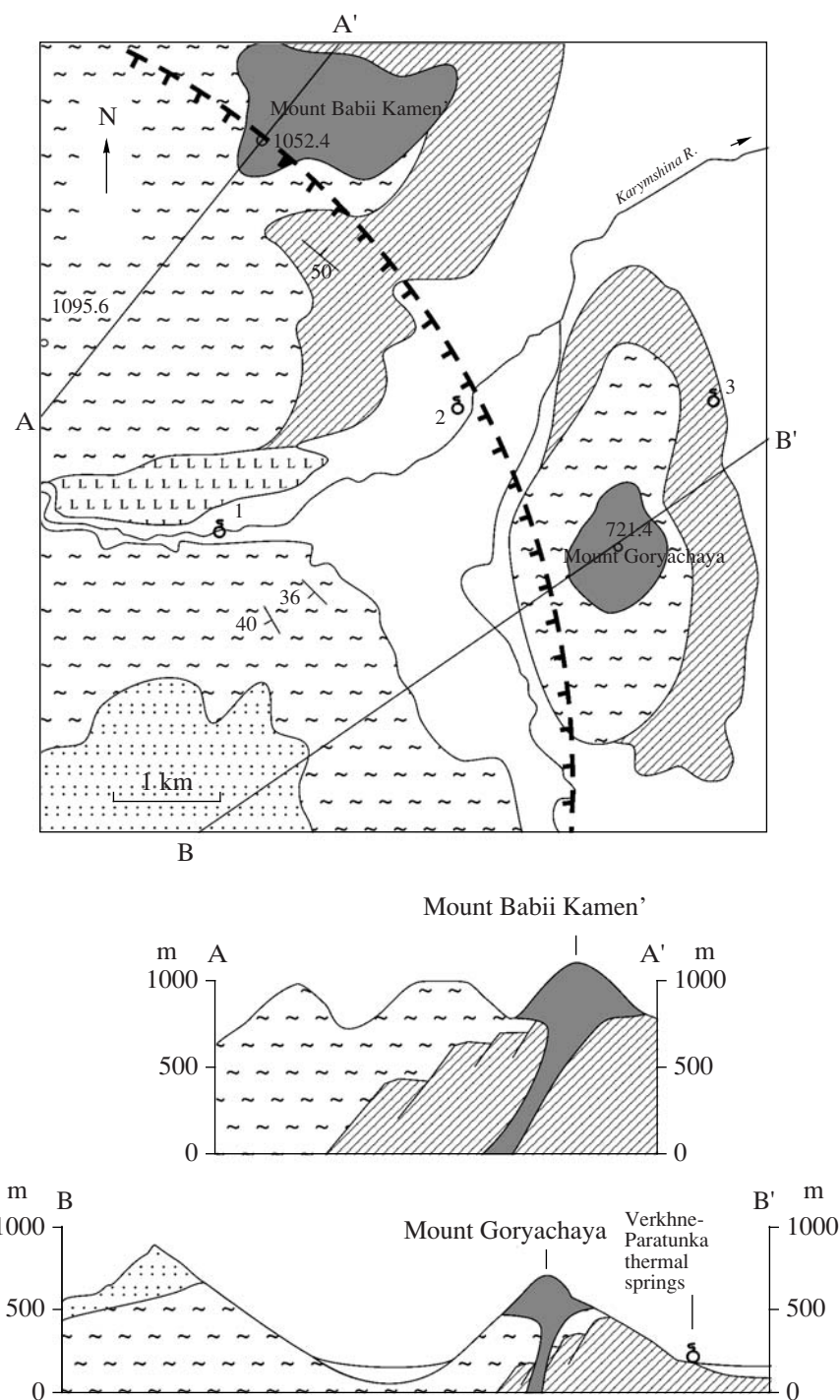


Fig. 10. Geological structure and geological cross-sections through the Babii Kamen' area. For notation see Fig. 3A. Thermal springs: (1) Verkhne-Karymshina, (2) Karymshina, (3) Verkhne-Paratunka.

caldera rim in the east (Figs. 10, 11). The Verkhne-Paratunka thermal springs also seem to be related to the faults that bound the caldera on the east.

New views on the structural controls of ore deposits in the area of study. The area contains a whole series of deposits and mineral occurrences of the gold-silver formation extending in a northwest band

[10]. It is thought that mineral occurrences and deposits are localized in a zone of major northwest trending normal faults that traverse southern Kamchatka along the boundary of the transverse Nachiki fold-block zone [10, 14]. The above data throw a new light on the structural controls of gold and silver occurrences and deposits in the area of study. We hypothesize that these con-

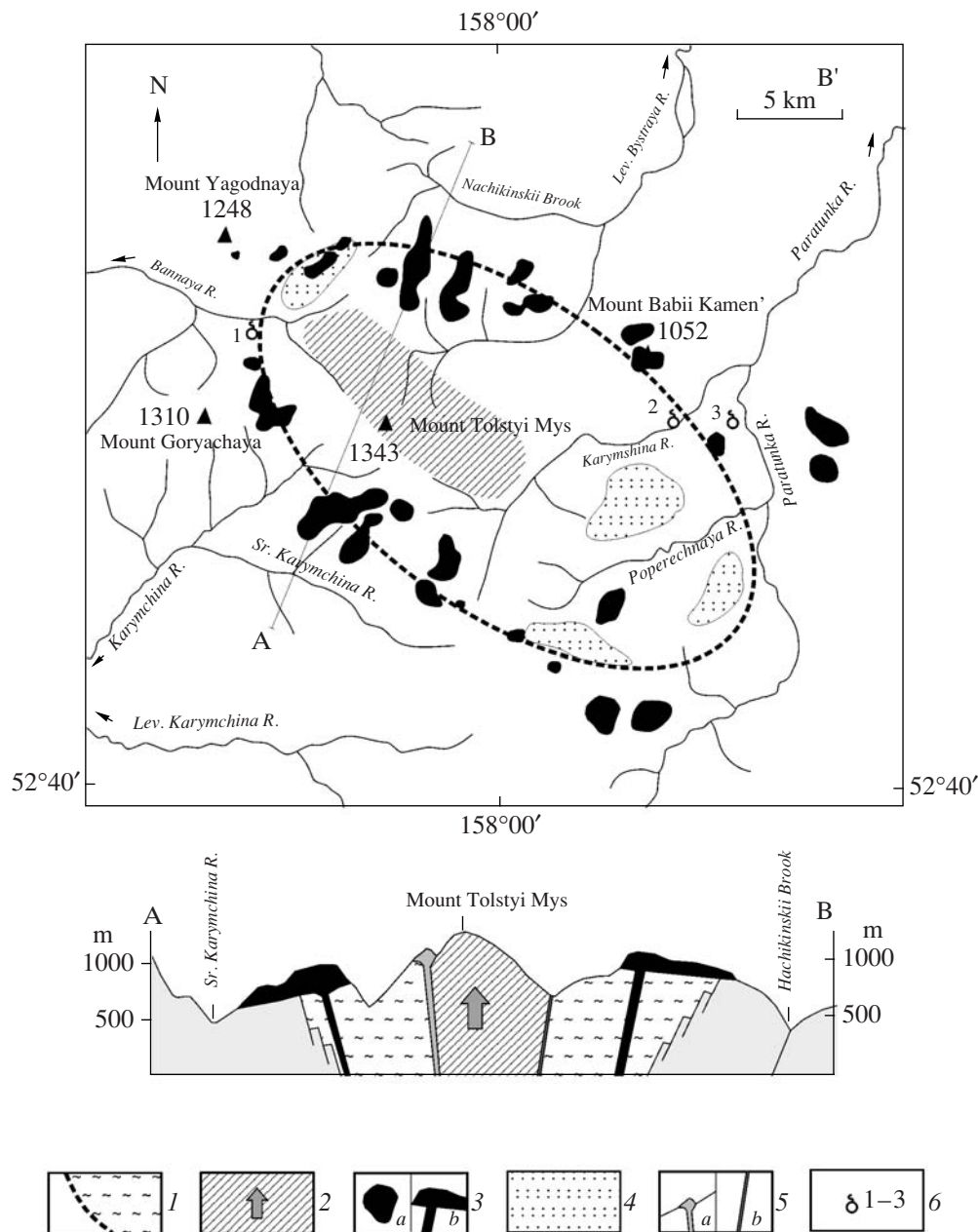


Fig. 11. A summary map showing the boundary of Karymshina caldera and its internal structure: (1) boundary of Karymshina caldera and the deposits that fill it (only shown in cross-section), (2) resurgent uplift, (3) rhyolite extrusions and associated lava flows: (a) on map, (b) in cross-section, (4) areas of detected lacustrine deposits (tuff sandstone and tuff aleurolite), (5) small volcanic structures composed of basaltic lavas (a) and ore veins (b) situated at edges of resurgent uplift, (6) thermal springs: (1) Bol'she-Bannaya, (2) Karymshina, (3) Verkhne-Paratunka.

trols are exerted by the faults that bound the caldera, as well as by the faults that bound the resurgent uplift situated in the caldera. In particular, known mineral occurrences in the upper reaches of the Bannaya, Levaya Bystraya, and Karymshina rivers are located along the fault that bounds the resurgent uplift on the northeast. A detailed study of the structural controls of gold and silver deposits in the area of study is a task for the future. Special research is needed for the purpose,

but it seems to us evident that the generation of a major shallow magma chamber, the associated subsidence, and the subsequent emplacement of large volumes of acid magma have all been leading factors that gave rise to both hydrothermal and ore systems there.

CONCLUSIONS

(1) A new large caldera has been identified in the area of the Karymshina volcanic complex previously

recognized in southern Kamchatka [22], and its dimensions have been determined (15×25 km). The caldera is not identical with the volcanotectonic depressions identified previously in the area of study, viz., the Karymshina [12] and Bannaya–Karymshina [22] depressions, so it has been given a new name, the Karymshina caldera.

(2) A tectonic uplift has been reconstructed in the northwestern part of this caldera, the uplift being regarded as a resurgent dome. The uplift has been found to be 4 by 12 km in size and to be elongate northwest. The uplift amplitude was estimated as 200 m. The uplifted block is bounded by straight northeast and northwest trending faults. We also reconstructed the boundary of a lake that had existed in the caldera south of the resurgent uplift.

(3) It was found that the Karymshina rocks (mostly acid tuffs and ignimbrites) that fill the caldera are everywhere adjacent to the lavas that compose the volcanoes of mounts Goryachaya, Yagodnaya, Levaya Karymshina, etc., which extend in a band trending northwest along the western boundary of the caldera. It has thus been unambiguously established that the above volcanoes are older and must be considered as evidence of a major volcanic phase that preceded the caldera generation.

(4) New data were obtained on the setting of the rhyolite domes widely abundant in the area of study. It was shown that they are mostly confined to the boundaries of the caldera and to the boundary of the resurgent dome situated in it. Most of the domes were emplaced much later following caldera generation, they have ages of 0.5–0.8 Ma [19, 20], and they should be regarded as a consequence of postcaldera volcanism. We also identified a postcaldera basaltic volcanic phase whose manifestations are strictly confined to the boundary of the resurgent dome.

(5) An approximate volume of material erupted during the generation of the caldera has been calculated, viz., about 825 km^3 , which makes a weight of 2×10^{15} kg. This eruption should therefore be regarded as the largest so far known to have occurred in Kamchatka and be classed among the great eruptions worldwide [28].

(6) The structural setting of the present-day hydrothermal systems in the area of study has been revised. It is shown that all larger hydrothermal systems (the Bol'she-Bannaya, Karymshina, and Verkhne-Paratunka ones) are confined to the boundaries of the Karymshina caldera. A new approach has also been advocated for determining the controls of the mineral occurrences and ore deposits known in the area. It is shown that the identification of the Karymshina caldera makes it possible to regard these ore deposits as a consequence of the existing large magma chamber above which the caldera was generated.

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